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13. ABSTRACT (Maximum 200 words) Under monotonically increasing compressive loading, polycrystalline ice undergoes a transition from ductile to brittle behavior upon increasing the strain rate to above a critical level. Correspondingly, the dependence of the failure stress on the strain rate changes from strongly positive to weakly negative; i.e., from strain rate hardening to moderate strain rate softening. Also, upon reaching the transition, the failure stress becomes dependent upon grain size, increasing as the grain size decreases. These characteristics indicate that different deformation mechanisms operate on either side of the transition. They indicate further that the transition marks the point at which the ice reaches its highest strength. In practical terms the ductile-to-brittle transition sets the maximum force a moving ice cover (e.g., on a river) exerts against an obstacle (e.g., a bridge pier). The problem, therefore, is to understand the origin of this transition. To this end a systematic experimental investigation was carried out at -10°C on columnar, fresh-water ice. The work was guided by the hypothesis that the transition occurs when cracks, nucleated during loading, begin to propagate. The hypothesis was verified.					
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THE DUCTILE TO BRITTLE TRANSITION IN POLYCRYSTALLINE ICE UNDER COMPRESSION

FINAL REPORT

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AUGUST 17, 1993

U.S. ARMY RESEARCH OFFICE

DAAL03-90-G-0141

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Final Report

1. Problem Statement

Under monotonically increasing compressive loading, polycrystalline ice undergoes a transition from ductile to brittle behavior upon increasing the strain rate to above a critical level. Correspondingly, the dependence of the failure stress on the strain rate changes from strongly positive to weakly negative; i.e., from strain rate hardening to moderate strain rate softening. Also, upon reaching the transition, the failure stress becomes dependent upon grain size, increasing as the grain size decreases. These characteristics indicate that different deformation mechanisms operate on either side of the transition. They indicate further that the transition marks the point at which the ice reaches its highest strength. In practical terms the ductile-to-brittle transition sets the maximum force a moving ice cover (e.g., on a river) exerts against an obstacle (e.g., a bridge pier).

The problem, therefore, is to understand the origin of this transition.

To this end a systematic experimental investigation was carried out at -10°C on columnar, fresh-water ice. The work was guided by the hypothesis that the transition occurs when cracks, nucleated during loading, begin to propagate.

2. Most Significant Results:

1. Under uniaxial compressive loading across the columns, grain boundaries crack when inclined to the loading direction. From these "parent" cracks extensions form along the loading direction. These extensions are termed wing cracks. Wing cracks form on both sides of the transition. Under increasing stress at strain rates above the transition rate, the wings lengthen in a stable manner and eventually split the material into a number of rather crack-free pieces. The wing cracks do not propagate under increasing stress at strain rates on the ductile side of the transition. The hypothesis is thus verified.

2. Crack-tip creep suppresses wing crack growth. For instance, crack growth can be stopped by holding a wing crack under constant stress for a sufficiently long time.

3. The transition strain rate increases with decreasing grain size and is consistent with functionality of the form $(\text{grain size})^{-3/2}$.

4. These results can be explained in terms of the competition between the build-up and the relaxation of stresses at the tips of the wing cracks. At high strain rates the build-up dominates and the cracks propagate. At low strain rates the relaxation dominates and the cracks are "blunted". The transition strain rate, $\dot{\epsilon}_{D/B}$, can thus be modeled by incorporating the crack size (which is set by the grain size, d) and the resistance to creep, to fracture and to frictional sliding across the surface of the inclined, parent crack. Accordingly,

$$\dot{\epsilon}_{D/B} = \frac{4ZBK_{IC}^3}{3\pi f(1-\mu)d^{3/2}}$$

where Z is a dimensionless constant, B is the co-efficient from the power law describing secondary creep ($\dot{\epsilon} = B\sigma^3$) K_{IC} is the critical stress intensity factor for mode-I crack growth, μ is the co-efficient of sliding friction for ice on ice and f is size of the creep zone relative to the parent crack.

A detailed description of the above work may be obtained from the papers listed below.

5. The experiments have also revealed that the transition strain rate depends upon confinement. Under biaxial loading across the columnar grains, $\dot{\epsilon}_{D/B}$ first increases and then decreases with increasing confinement. This effect is reported in Progress Reports 5 and 6. It will be explored further at a later date. Meanwhile, the effect is being analyzed.

3. Publications

3.1 with support from this grant only:

"A Preliminary Investigation of the Ductile-Brittle Transition in Columnar S2 Ice Under Compression"

R.A. Batto and E.M. Schulson

Proc. IAHR Ice Symp. (1992) 1021-1034.

"On the Ductile-To-Brittle Transition in Ice Under Compression"

R.A. Batto and E.M. Schulson

Acta metall. mater. 41 (1993) 2219-2225.

"Ductile-to-Brittle Transition in Ice Under Compression: Grain Size Effect"

R.A. Batto and E.M. Schulson

ASME - AMD 163 (1993) 229-234

"An Investigation of the Ductile-Brittle Transition in Columnar S2 Ice Under Compression"

R.A. Batto

Master of Engineering Thesis, June 1992.

3.2 with minor support from this grant and major support from another:

"The Brittle Compressive Failure of Fresh-Water Columnar Ice Under Biaxial Loading"

T.R. Smith and E.M. Schulson

Acta metall. mater. 41 (1993) 153-163.

"Ductile Ice"

E.M. Schulson and G. A. Kuehn

Phil. Mag. 67 (1993) 151-157.

4. Scientific Personnel Supported:

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